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ScienceDirect

Procedia CIRP 43 (2016) 208 – 213

www.elsevier.com/locate/procedia

14th CIRP Conference on Computer Aided Tolerancing (CAT)

Automating robot planning using product and manufacturing information

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Abstract

Advances in sensing, modeling, and control have made it possible to increase the accuracy of robots, and enable them to perform in dynamic environments. Often, performance deficiencies are not evident until late in the development of the manufacturing process, which delays the beginning of production and may cause damage to parts that have already undergone costly manufacturing steps. The goal of this research is to determine if a robot can meet manufacturing requirements, how to optimally plan robot activities, and to monitor robot processes to track performance. To achieve this, representations of product and manufacturing information and robot capabilities should be carried through the design, process planning, production, and analysis phases. Standards for the exchange of this information have been developed, such as ISO 10303 Part 242 for semantic product and manufacturing information and device kinematics, and the Robot Operating System Industrial specification for robot modeling, path planning, and execution. This paper surveys the relevant technologies and standards needed to enable automated deployment of robots in new application areas.

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing

Keywords: robotics; assembly; product and manufacturing information; tolerances; path planning; process planning

1. Introduction

Continual productivity increases have enabled sustained manufacturing growth, with automation playing a key role. Future growth requires extending automation into applications that have proved difficult to automate due to complex and unpredictable environments. Such applications can benefit from the flexible nature of robotics, but the poor accuracy of robots compared with traditional dedicated automation has limited their deployment. Advances in sensing, modeling, and control have made it possible to increase the accuracy of robots, and these technologies make them responsive to noisy and dynamic environments. As robots are brought into these environments, it is important to be able to predict how well they will perform. Often, performance deficiencies are not evident until late in the development of the manufacturing process, which delays the beginning of production and may cause damage to parts that have already undergone costly manufacturing steps. The goal of the research reported here is to determine if a robot can meet manufacturing requirements, how to optimally plan robot activities, and to monitor robot processes to track performance. To achieve this, representations of product and manufacturing information, and robot capabilities should be carried through the design, process planning, production, and analysis phases. Standards for the exchange of this information have been developed, such as ISO 10303 Part 242 for semantic product and manufacturing information and device kinematics [1], and the Robot Operating System Industrial specification for robot modeling, path planning, and execution [2]. This paper surveys the relevant technologies and standards needed to enable automated deployment of robots in new application areas.

2. Product and Manufacturing Information in Design

Manufacturing tolerances are defined by the amount a feature is allowed to vary from the nominal. Assigning geometric and dimensional tolerances to a manufactured part is a tradeoff between design and manufacturing. Engineering design assigns tolerances based on fit and

Peer-review under responsibility of the organizing committee of the 14th CIRP Conference on Computer Aided Tolerancing
doi:10.1016/j.procir.2016.02.139

function. Manufacturing considerations for tolerances are machining process selection, the cost for achieving the engineering tolerances, part inspection, and the assembly feasibility of parts [3, 4]. Tight tolerances usually result in better performance but higher cost. Loose tolerances reduce the cost of manufacturing at a cost of poor performance and proper assembly. Tolerances can be assigned to a part through either tolerance *synthesis* or tolerance *analysis* [5, 6]. Tolerance synthesis considers the complete tolerance and functionality for an assembly and assigns tolerances to its individual parts. Tolerance analysis estimates tolerances for individual parts and computes the range of tolerances for an assembly. Tolerances have to be transferred to the manufacturing and inspection processes in such a way that the functionality of the part or assembly is not compromised. Tolerances are part of a subset of information known as Product and Manufacturing Information (PMI). PMI includes the annotations that define Geometric and Dimensional Tolerances (GD&T) on Computer-Aided Design (CAD) models along with non-geometric data such as surface texture specifications, finish requirements, process notes, material specifications, and welding symbols. PMI is used to help define product geometry and product specifications [7]. GD&T is a symbolic language used to communicate tolerances on manufactured parts. The industry standards for presentation of GD&T in views in 3D space, also used in CAD systems, are ASME Y14.41-2012 [8], and ISO 16792:2006 [9], both of which define digital product definition data practices. The industry standards for the syntax and semantics of GD&T are ASME Y14.5-2009 [10] and ISO 1101:2012 [11]. The ASME and ISO standards for GD&T have been used since the 1940s and were developed to address problems related to describing variations in part and assembly geometry [12]. Common types of GD&T include geometric tolerances on flatness, position, perpendicularity, surface profile, and circular runout, and dimensional tolerances on length and diameter.

Figure 1 defines syntax and semantics for the flatness tolerance applied to the top surface of a simple object. The top diagram labeled "This on the drawing" shows the syntax of a flatness tolerance on a 2D drawing with rectangular frame containing a symbol and number pointing to the surface to which the tolerance is applied. The symbol for the flatness tolerance is a parallelogram and "0.15" refers to the width of the tolerance zone. The bottom diagram labeled "Means this" defines the semantics of the flatness tolerance where the toleranced surface must lie between two parallel planes 0.15 units apart shown in grey. Therefore, the surface of the manufactured part has to be contained within a tolerance zone that is 0.15 units thick. In CAD systems, PMI annotations for tolerances are associated with the relevant surfaces and edges depending on the tolerance type. An important distinction shown in the two drawings is that between PMI *representation* and *presentation* [13]. PMI *representation* (also known as semantic PMI) includes all of the information necessary to represent GD&T without any graphical elements. PMI representation is associated with CAD model geometry and is computer-interpretable for downstream consumption by applications for manufacturing, measurement, inspection, and other processes. PMI representation does not contain any information regarding how it should be visually depicted. PMI *presentation* (also known as graphical PMI) consists of drawing elements such as lines and arcs preserving the appearance of the GD&T annotations. PMI presentation is intended to be human-readable, but not intended to be computer-interpretable and does not carry any representation information. PMI presentation corresponds to the callout in the top diagram "This on the drawing" in Figure 1.

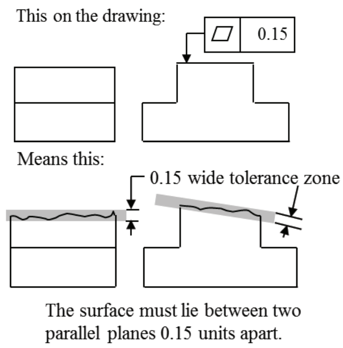

Figure 1: Flatness tolerance syntax and semantics as defined in ASME Y14.5 [10].

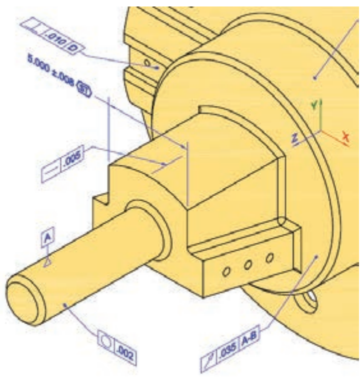

Figure 2: CAD model with GD&T annotations

Figure 2 shows a CAD model with representative GD&T annotations, based on ASME Y14.5 and Y14.41, including dimensions, tolerances, geometry control tools, tolerance zones, datum reference frames, and datum features [14]. This model is part of a collection of test cases used by the Computer-Aided Technologies Implementer's Forum (CAx-IF) [15], a group of industry participants working to ensure software compatibility. The annotations are representative constructs; however, the part is not fully toleranced or functional for tolerance purposes.

ISO 10303, the STandard for Exchange of Product model data (STEP), is a family of standards defining a methodology for describing product data throughout the life cycle of a product [16, 17]. A STEP *Application Protocol*

(AP) specifies an information model for a particular technical or engineering domain. CAD systems implement APs as import and export interfaces for product data. STEP AP242, known as Managed Model Based 3D Engineering, is a new STEP specification that contains both PMI representation and presentation of GD&T [18]. In addition to product geometry it also contains many new capabilities that enable the machine-readable representation of manufacturing and assembly information, such as part tolerances, surface finish, and manufacturing process information [19, 20]. This information is for interoperability with downstream applications such as manufacturing and inspection. AP242 contains both the PMI representation and presentation of GD&T. STEP AP242 also contains a kinematics model that can be used to describe kinematic topology, structure, state, motion representation, and analysis control and results [21]. The geometry of complex machine tools can be modeled and associated with links, joints, and loops that define the kinematic topology. Kinematic structure defines pairs including planar, cylindrical, prismatic, gear, rack and pinion, revolute, rigid link, rolling surface, screw, sliding, spherical, surface, and universal. The state of the kinematic pairs can be defined along with their motions.

3. Robot Performance

The PMI test case in Figure 2 indicates a circularity callout applied to the cylindrical protrusion that stipulates that all points on the surface of the cylinder lie within the surfaces of two concentric cylindrical surfaces separated by no more than 0.002 inches (0.05 mm). The diameter of acceptable cylinders may vary by as much as 0.004 inches (0.1 mm) in a given direction. In order to determine if a particular robot can achieve the tolerance requirements and how to plan optimal motions, robot performance metrics are needed. The most common performance metric for industrial robots is *repeatability*, or the consistency with which the robot returns to a given point. This is due to the prevalence of the method of *teach programming*, where the robot is physically brought to a series of poses that are recorded for later playback in a programmed sequence. A typical repeatability quoted by industrial robot manufacturers is 0.02 mm. Teach programming can be time consuming, and requires a person to do the teaching while the robot is taken out of production. While it is cost effective for high-volume applications, it is often faster to do small jobs manually. In contrast, *off-line programming* uses models of the parts, robot, and work volume to generate sequences of nominal robot poses, relying on the *accuracy* of the robot to achieve the computed points. This is analogous to the primary method of programming machine tools, using CAD data and a Computer-Aided Manufacturing (CAM) system. However, due to their construction, robots are typically much less accurate than machine tools. While accuracy figures are not typically reported, they range from 10 to 100 times the repeatability [22], so we can estimate uncompensated accuracy to be on the order of 1 mm. Off-line programming must be supplemented with other techniques to increase the accuracy to acceptable levels. Calibration can be done, but errors vary considerably throughout the work volume due to flexing of robot links, so calibration tables must be generated at many locations and orientations. This process is known as *error mapping*. Because robots typically have low stiffness and will deflect appreciably under loads, error maps are only effective when developed under loaded conditions. If these vary during an application, error mapping may be ineffective. *Process sensing* is effective under varying loading conditions, because the actual location of the robot is measured and deviations can be adjusted in real time. This requires an increased investment in sensing technology, and possible changes in the process to reduce noise or occlusions. A hybrid technique is to use a set of taught points at key areas in the work volume, benefitting from high repeatability, and calculating offsets from these taught points based in sensor data from cameras or other vision systems. Robots have been successfully used in this way for semiconductor chip placement, with placement accuracy requirements well below the 1-mm level.

4. Robot Modeling

Robot accuracy is negatively influenced by many sources. The robot’s structure and motion constraints of its components relative to one another (its kinematics) may only be approximately modeled. The robot will deflect under its own weight, and in response to applied loads. Temperature variation in the environment, and localized heating due to friction or proximity to heat sources in the process, can cause non-uniform thermal growth. Some of these error sources are systematic, and can be canceled out through techniques such as error mapping described in Section 3. With more sophisticated models, errors can be predicted and compensated for, especially when sensors are used. The inclusion of uncertainty in kinematic modeling is important for translating design intent into robot motion. Hedlind et al. identified existing limitations and described new methods for achieving this and how it can be modeled in STEP [23]. In addition to basic models of kinematic structure, modeling includes dynamic properties such as inertia and friction, stiffness models that account for deflection under load, and thermal models for expansion. Inaccuracy in objects and resources in the workspace of the robot also contribute to overall uncertainty in applications. Durant-White developed a framework for representing and transforming this uncertain geometry throughout a robotic system [24]. The following sections describe some methods for modeling robots themselves, including uncertainty.

4.1. Homogeneous Transforms

Robotic applications rely on representations of the position and orientation of objects in the workspace, their poses. In our three-dimensional world, position and orientation each have three degrees of freedom. For position, a Cartesian X-Y-Z system is typically used, although other representations are possible, such as cylindrical or spherical coordinates. For orientation, many systems are commonly used, including roll-pitch-yaw, Euler angles, rotation matrices, and quaternions. A common pose representation that combines position and orientation is the homogeneous transform matrix (HTM), which uses a three-element Cartesian position representation and a nine-element rotation matrix, padded to make it a square matrix and invertible with no special treatment. The HTM representation is:

$$\begin{bmatrix} X_x & Y_x & Z_x & P_x \\ X_y & Y_y & Z_y & P_y \\ X_z & Y_z & Z_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where the *X*, *Y*, and *Z* columns are the unit vectors of the rotation, and the *P* column is the position vector. This is purely a formal representation; in practice, calculations are done with more efficient representations once the formal HTM analysis has been done. A full treatment of pose representations is found in [25]. An HTM representation of infinitesimal displacements and rotations can be used for uncertainties in a pose. This approach requires that errors be measured in a Cartesian reference frame, for example from a laser measurement system or ball bar according to standard performance tests [26]. Denoting infinitesimal displacements in *X*, *Y*, and *Z* as δ_x, δ_y, and δ_z, respectively, and likewise infinitesimal roll, pitch, and yaw as ϵ_x, ϵ_y, and ϵ_z, the uncertainty HTM becomes:

$$\begin{bmatrix} 1 & -\epsilon_z & \epsilon_y & \delta_x \\ \epsilon_z & 1 & -\epsilon_x & \delta_y \\ -\epsilon_y & \epsilon_x & 1 & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Uncertainty HTMs can be concatenated in a series, resulting in a compound transform that includes error effects. This is the approach taken by Schmitz et al [27], who determined the overall uncertainty of a measurement system composed of components for which individual uncertainty HTMs were measured. The cumulative error HTMs can be combined into a single HTM that can be applied to the nominal transform. This single error transform can then be analyzed for its overall effect on the compound system.

4.2. The Unified Robot Description Format

The Robot Operating System (ROS) [28] is an open-source robot programming framework that provides communication infrastructure, message definitions, and support libraries for developing robotic applications. ROS includes packages for many robot, sensor, and gripper types, and an active developer community that continually contributes new packages. One part of ROS is the Unified Robot Description Format (URDF) for describing the kinematic, dynamic, and geometric properties of the links and joints that make up robotic devices. Figure 3 shows a sample of how this information is represented.

The `xyz` and `rpy` attributes of the `origin` elements for links and joints contain the information from HTMs. The other elements define dynamic properties such as mass and inertia of links, and friction and damping for joints. URDF supports many other types of information not shown in the example above, but no uncertainty is associated with any of the relevant elements. ROS does have the ability to annotate dataflows with uncertainty information in the form of (co)variance matrices included in the messages that constitute those dataflows. For instance, the message type `PoseWithCovarianceStamped` encodes both the HTM and the uncertainty as described in Section 3.1, with a Cartesian position, quaternion rotation, and an associated 6-by-6 covariance matrix for X, Y, and Z and rotations about these axes in a fixed reference frame (i.e., roll, pitch, and yaw). The poses are timestamped so they can be consistently associated with other timestamped data. However, this support is currently mostly used for data originating from software components that interface with sensors such as inertial measurement units, absolute localization and environment monitoring systems, and by sensor fusion components such as those producing odometry for mobile platforms, robot localization estimates, and object poses from image streams.

```
<link name="link1">
   <inertial>
     <origin xyz="0 0 0.5" rpy="0 0 0"/>
     <mass value="1"/>
     <inertia ixx="100" ixy="0" ixz="0"
              iyy="100" iyz="0" izz="100"/>
   </inertial>

   <collision>
     <geometry>
       <cylinder radius="1" length="0.5"/>
     </geometry>
   </collision>
</link>

<joint name="joint1">
    <origin xyz="0 0 1" rpy="0 0 3.1416"/>
    <parent link="link1"/>
    <child link="link2"/>
    <dynamics damping="0.0" friction="0.0"/>
    <limit effort="30" velocity="1.0"
           lower="-2.2" upper="0.7"/>
</joint>
```

Figure 3. Sample Unified Robot Description Format (URDF) showing how links and joints are represented.

Other core components of ROS responsible for runtime robot state and environment modeling do not make use of uncertainty information, nor are they able to process or produce it, resulting in a loss of this information as soon as it is received by any of those components. The `TF` transform library responsible for keeping track of all coordinate frames in an application at runtime is one such core component. As many motion planning pipelines in ROS use it, addressing this would remove a significant obstacle for the application of ROS in precision manufacturing pipelines. A supplemental package, `uncertain_tf`, does add support for uncertainty in `TF` [29]. Uncertainty is modeled similarly to the `PoseWithCovarianceStamped`, using Euler angles to represent orientation. The `uncertain_tf` authors note that calculating covariance matrices from Euler angles is not the best way to represent and propagate orientation uncertainty. Franaszek et al. explain the propagation of orientation uncertainty in more detail in [30], using an angle-axis representation; this could form the basis for extending TF with uncertainty in a canonical way. While homogeneous transforms and formats such as URDF provide quantitative descriptions of the kinematic and dynamic properties of a robot, linking these properties to functional capabilities and mapping these capabilities to high-level descriptions of tasks remains a research problem. Kunze et al. noted this semantic gap between high-level action instructions such as "pick up the cup with the right hand" and lower-level properties such as those modeled by URDF [31]. This gap is being bridged by standards such as IEEE-1872:2015 from the Ontologies for Robotics and Automation working group [32].

5. Robot Path Planning

The uncertainty described earlier relates to final robot poses, but uncertainty along a robot path is important for applications such as seam welding, adhesive application, or assembly insertion. Carlson et al [33] showed how both part variation and robot variation are taken into account when automatically planning collision-free robot motions. Path tolerances should also be used during control, affording the robot controller the opportunity to adjust motion parameters to ensure that paths remain within the required tolerances, or to alert the supervisory system that the requested tolerances cannot be achieved. ROS supports the association of pose and path tolerances with motion requests, where tolerances apply to joint positions (linear or angular), velocities and accelerations, Cartesian position and orientation, and also to the time duration of the motion. ROS provides a deterministic path planner that guarantees adherence to geometrically constrained paths, and can exploit kinematic redundancy when a robot has more degrees of freedom than needed by the application. This motion planner, Descartes [34], supports the specification of pose and path tolerances in Cartesian space, for both position and orientation.

6. Association with Product and Manufacturing Information

An end-to-end system that demonstrated the association of machine uncertainty to product tolerances was built by Fesperman et al [35]. This system, the Virtual Machine Tool (VMT), took models of five-axis machine tool errors, ran a simulation of a process plan, and measured the resulting errors on the generated part model. Geometric error modeling was done for such sources of error as linear positioning error along an axis direction, and straightness error normal to an axis direction. This information was represented in the draft ASME B5.59 format [36]. Controller error modeling was done for effects due to mass, damping, friction, filters, and control gains, in extensions to ASME B5.59 compatible with its XML format. Machining tool paths were generated and ran through error models, producing a workpiece error file that was fitted to features for subsequent analysis. The VMT exemplifies the use of standard formats for error modeling to generate information about the effects on production parts. STEP AP 242 introduces the possibility of automating several steps:

- Generating process plans based on PMI requirements, e.g., selection of robots, and placement of parts in sufficiently accurate areas of the work volume. AP 242 provides semantic GD&T in machine-readable format.
- Extending process plans with tolerance requirements. For robots, ROS/Descartes provides this capability for both joint and Cartesian moves.
- Determining that parts fulfill design requirements, using AP 242's semantic GD&T.

The lack of standard information models as an obstacle to automated end-to-end translation of design intent into process planning, production, and inspection has largely been eliminated. The VMT demonstrated that this is possible for the most part for machining, and pointed out information modeling needs that have recently been addressed by STEP AP 242 and ROS. Plans for demonstrating this end-to-end application of standard information models are currently underway in pilot projects.

7. Conclusion

PMI defines requirements for fit and function that inform process planning and quality assurance. GD&T is an important part of PMI, with symbols and meanings standardized in ASME Y14.5 and ISO 1101. Recently, ISO 10303 AP 242 has added semantic PMI to computer-aided design interchange, allowing GD&T requirements to be automatically carried through from design to process planning and inspection without the need for human interpretation. This opens up the possibility to automate the selection, programming, and operation of robotic systems and ensure that the results achieve the product requirements. To do this, models of robot performance need to include representations of accuracy and uncertainty, and sufficient kinematic and dynamic information to optimally place operations in their work volumes. During operation, tolerances need to be included on paths and goals to confirm confident performance and make real-time adjustments if necessary. ROS provides this modeling capability and message support, with the ROS-Industrial Consortium working to bring this from research to production.

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